High Frequency Electronic Packaging Technology

Martin Herman, Lynn Lowry, Karen Lee, Elizabeth Kolawa, Ann Tulintseff
Jet Propulsion Laboratory, California Institute of Technology
4800 Oak Grove Drive
Prisadenn,CA91109

Kurt Shalkhauser
NASA Lewis Research Center
21000 Brookpark Road MS 54-8
Cleveland, 01144135

John Whitaker
Ultrafast Science Laboratory
University of Michigan
Ann, Arbor, MI 48109

Melinda Piket-May
Electrical & Computer Engineering Department
University of Colorado
Campus Box 425
Boulder, CO 80309

ABSTRACT

Commercial and government communication, radar, and information systems face the challenge of cost and mass reduction via the application of advanced packaging technology. A majority of both government and industry support has been focused on low frequency digital electronics. However higher operating frequencies for both digital and analog circuits will be required for future systems. *By* 1997, ***the projected domestic captives sales for Multichip Modules (MCMs) will be over a half billion dollars.*** Therefore, it is critical to develop the technical infrastructure necessary to support this emerging industry. This paper discusses the kick-off of a JPL sponsored Director's Discretionary Fund project to specifically address the needs of high frequency packaging and our coordination with NA SA's Lewis Research Center's ongoing efforts to provide commercial high frequency packaging technology. We are working with industry, universities, and DoD to characterize and analyze high frequency multichip module packages. Our emphasis is on Materials Science and Radio Frequency (RF) Engineering with a goal to develop CAD tools and characterization techniques which can be readily transferred to industry to accelerate the development of *manufacturable* high frequency packaging technology.

INTRODUCTION

It is projected that in the next 5-10 years, commercial applications in the high frequency regime (1 GHz to 100 GHz) will expand in areas which include: cellular communications, telecommunications, automotive radar for intelligent vehicular highway systems, advanced computing, aircraft radar, direct broadcast satellites, communication networks for the information superhighway just to name a few. This is due to the desire to increase our information capacity and at the same time decrease system mass and cost. It was estimated [1] that by 1997 merchant market value and domestic captive sales for multichip module (MCM) packages would be a half billion dollars.

During a JPL-hosted High Density Packaging Workshop [2] the consensus among industrial participants was that NASA funding in the area of high frequency packaging technology would be timely and beneficial to U.S. industry as a stimulus. In addition, the majority of resources being invested by industry in high density packaging technology development are focused on low frequency (<200 MHz) applications (Figure 1). A challenge which industry, DoD, NASA and JPL must meet is the development of high-density, high-frequency packages which are manufacturable, provide excellent electrical/mechanical performance, and long term reliability. The JPL/NASA team offers a non-competitive forum to coordinate on-going and future efforts to help accelerate and in partnership with industry contribute to this technology.

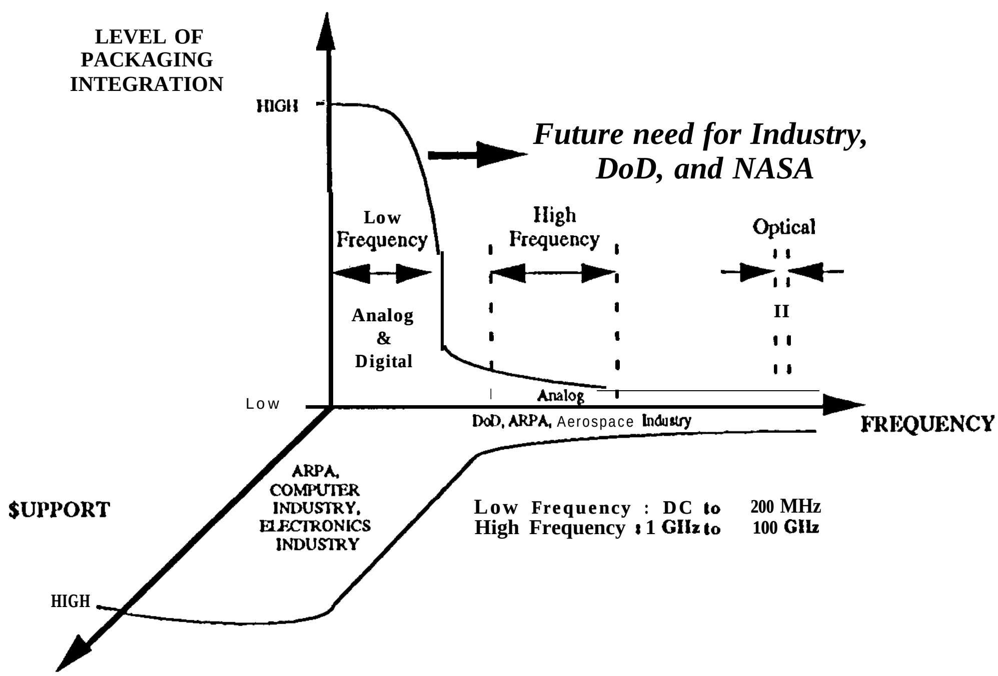

Figure 1. Current funding trend for advanced electronic packaging technology

We have initiated the development of high frequency packaging technology which has drawn a large response from the user community [3] and was documented for public review in [4]. In this paper we will describe new techniques to characterize MCMS using non-invasive optoelectronic probing techniques, development of 3-D electromagnetic CAD tool which will allow packaged devices and networks to be accurately analyzed thereby reducing development costs, the development of MMIC packages for phased array applications, and the use of novel multi-material" systems to enable new package structures which are reliable and most of all manufacturable.

Background

Microelectronic packaging provides four basic functions:

- Power Distribution
- Signal Distribution
- Heat Dissipation
- Environmental Protection

High density electronic packaging refers to the incorporation of multiple integrated circuits, as bare die and passive components on a common interconnecting substrate. This format is commonly referred to as a multichip module (MCM). Significant improvements in circuit density are attainable (1 O-30X), as compared with printed circuit board technology.

Signal distribution becomes a major challenge as the frequency and packaging densities increase. Stray (RF) radiation in the form of crosstalk and package moding become limiting factors which must be addressed in order to preserve performance. The interconnecting networks into and out of the package must have low loss characteristics and be matched to the impedances of the adjacent networks. 3-D high density formats which use multilayer materials systems and embedded components further complicate signal propagation characteristics and thermal management issues.

Technical Challenges

In the development of a high-density high-frequency packaged module, the designer selects a variety of individual devices (transistors, diodes) and integrated circuits (Monolithic Microwave Integrated Circuits-MMICs) which have been characterized in an open air environment. The design is usually formulated using commercially available microwave circuit programs which are limited in their ability to correctly analyze the interaction of the active components within a closed environment of the package. Furthermore, almost every package configuration is unique to the particular problem at hand. Commercial CAD to analyze active RF networks in a packaged environment is not available. ***This is a major gap which we have begun to address.*** For high frequency packaging networks we need to employ 3D electromagnetic analysis combined with non-linear effects of active circuits to determine operation and prevent stray radiation from degrading performance due to crosstalk or package moding. We must develop a technique which can be applied to a variety of MCM structures and active circuits. Finally, this technique should be amenable to being integrated to existing software packages in order to facilitate their use in industry.

The question of how does one characterize an enclosed (packaged) module when it is not performing as expected becomes more complicated the higher the system operating frequency. For low frequency, built-in-test (BIT) structures can be employed, However, for high frequencies where there are analog as well as digital signals, BIT structures may not give enough information on what the problem is and how to solve it. One could open the package and check around; however, the complete enclosed structure may be necessary in order to have the inhibiting phenomena to occur. The solution is a technique which can be non-invasive, preserve the enclosed package environment and provide both spatial and temporal resolution to probe the entire space and look at a full spectrum. ***Our approach is to employ optoelectronic probing.*** The technique is simple in principle and can be applied to a manufacturing line as well as in the development laboratories.

Although MMIC devices are maturing and becoming more available to potential users, their application in systems remains severely impeded by lack of high-frequency packaging. In order to successfully transition these small, fragile circuits from the laboratory environment to real-world systems, such as phased array antennas, engineers at NASA's Lewis Research Center and JPL have been developing advanced packaging through technically aggressive R&D programs. Novel solutions to provide high frequency packages for MMIC devices are presented.

Up to this point we have concentrated on the electrical aspects of high frequency packaging. Just as important are the material parameters which comprise the package and influence its reliability, manufacturability and cost. At high frequencies the electrical signal propagates closer to the dielectric/conductor interface, consequently the interface structure and chemistry significantly impacts the electrical performance. Thin film coatings for circuit protection and thermal management also come under this category. A variety of interface systems are being investigated and this constitutes a large portion of our effort.

RF PACKAGING TECHNOLOGY

As stated previously, the current work which is being funded concentrates on the development of optoelectronic techniques to characterize MCMS, 3-D electromagnetic simulator tool which can accurately analyze packaged networks and help decrease development costs and the status in the development of MMIC package technology.

Optoelectronic Probing

As industry develops advanced high frequency MCMs, there is an urgent need to characterize the entire module for functionality quickly and inexpensively. One approach is to add numerous detectors and I/O ports to the module in order to monitor each discrete device. This drives up development, fabrication and test costs, and increases mass. An alternative approach which has not been applied to electronic packaging involves the use of optoelectronic probes, based on either electro-optic or photoconductive principles. In electro-optic probing, a thin dielectric ti p (fabricated from materials whose index of refraction changes with the intensity of an RF field passing through them) could be used to measure the amplitude and phase of electric fields within the volume of a package. Alternativel y, photoconductive gates (which briefl y pass current across a small gap charged by an electric field when illuminated by an ultrashort-pulse laser) could be integrated with extreme] y small metal lines on a probe to scan an entire package volume with very high sensitivity, The data obtained could be used to quickly identify faulty parts and anomalous RF performance within the package structure.

Even though optoelectronic probing has never been used in the test and characterization of high density packages, the concepts which we will rely on have been demonstrated in measurements of individual MMICs [5, 6],

The group involved in high-resolution, optical] y-based measurement techniques resides in the Ultrafast Science Laboratory at the University of Michigan. For more than ten years researchers in this group have worked to develop electro-optic - and more recently, photoconductive - sampling techniques that have been applied to test and characterization of short-relaxation-tire e materials (semiconductors and superconductors), passive and active devices, and analog and digital integrated circuits. Using this foundation, the Michigan laboratory is developing the system that will be utilized for measuring both the electric field and time-resolved signals within enclosed circuits, Optically-based techniques have been used extensively for measurements in open architectures, both to resolve transients as short as 150 fs and to map out fields within circuits, However, no external technique has before attempted to address problems such as the identification of resonances or failed devices within packaged MCMS.

Optoelectronic probes, which would be fed by optical fibers and should have very little influence on the operation of the circuit under test, would enter the packaged device through openings much smaller than the wavelengths of the signals to be measured. Taking into account previous experience, it is anticipated that the probes should have sensitivity adequate to measure fields present in MCMS with analog sections driven with milliwatts of power. Furthermore, when used to obtain individual waveforms, a time resolution corresponding to a bandwidth of 100 GHz should be readily attainable. The probe will have dual-use capability from two standpoints: it will perform both field mapping and waveform acquisition; and it should be applicable to both analog and digital sections of MCMs.

The development process is taking place in two steps. Initial] y, in order to verify adequate sensitivity and to test the optoelectronic probe on a device with an analytically-known field pattern, existing probe designs are being mechanically modified in order to measure the field in a microwave cavity resonator. The second step will extend the applicability of the probe to a packaged MCM (most likely a transmit/receive module with analog and digital networks) which has its operation hindered by resonance/crosstalk effects.

Electromagnetic CAD Tool

Commercial CAD tools to analyze ***active RF*** networks in a packaged environment is not available. Therefore, we are currently investigating a new JPL concept called the Active Boundary Condition and employing the use of the JPL Cray capability to accelerate development. As part of the algorithm development, technology transfer to commercial microwave CAD packages will be important. The University of Colorado has experience with the integration of advanced electromagnetic software with commercial circuit analysis tools and will help accelerate this effort.

The basis of the analysis is a Finite Difference Time Domain (FDTD) algorithm which solves for Maxwell's equations. The FDTD techniques has received much attention in the open literature; however, the majority of this information is concerned only with passive structures. We will take advantage of the time domain aspects of FDTD and enable linear and nonlinear networks to be incorporated into the solution. Initial attempts to address this problem have idealized the active components modeled between two adj scent nodes. For low frequency applications this is probably an adequate solution; however, in the high frequency regime the physical device geometry and passive interconnect structure are distributed over many mesh points within the numerical grid thereby necessitating re-evaluation of the method of analysis.

MMIC Packaging for Phased Array Antenna Applications

NASA's Lewis Research Center's package development program focuses on MMICs operating in the 18.0 to 44.0 GHz frequency range, with interest in reconfigurable designs, flight qualification, and low-cost mass production. The packages are designed to withstand the challenging space environment of a communications satellite, but are directly applicable to a wide range of airborne and terrestrial systems.

Two contracts with industry examine various MMIC package configurations. The first contract, NAS3-25864, deals primarily with the development of a generic, or universal package and the attendant test fixturing that support a single MMIC chip. The package developed offers full hermeticity, mechanical device protection, heat removal from the device, and low insertion loss. This particular package is being carried through the environmental testing required for space qualification under NASA HQ Code Q funding.

The development of a single-chip package has moved rapidly from a research component to a marketable product. The package is constructed of high-purity ceramic with a metallic and base, with overall dimensions of only 0.28 by 0.28 by 0.05 inches. Radio frequency signals enter and exit the package through impedance-matched hermetic seals at opposite ends of the package. Ten bias and control lines are provided along the sides of the package. An additional feature of the package is its flexibility, whereby it may be refitted for different MMICs by modifications to on] y one of its four layers. Estimates pl ace the cost of a typical package at approximately twenty dollars for small quantities, with substantial savings under mass production.

A second packaging effort, NAS3-25870, is examining the feasibility of multi-element, or multi-circuit packages as they would be applied to advanced phased array antenna systems (Figure 2). This approach permits several MMICs to be placed in close proximity to one another in a single package to achieve the tight spacing required between the radiating elements of an antenna. Each MIMIC is installed in an individual compartment to eliminate crosstalk between chips and suppress electrical moding. An application-specific integrated circuit (ASIC) is included in the package to demultiplex a single serial data stream and thereby reduce the number of interconnect lines sent from a system controller. Interconnects between the ASIC and the RF MMICs are accomplished through multilayer interconnect located below the RF ground plane. This technique has permitted greatly-increased packaging density to be achieved.

The ongoing program will examine the performance of both single and multi-chip packages when operated in relevant space and aircraft environments. Additionally, emerging technologies such as fiber optics, multi-layer high-density interconnect, and self-correcting system-level integrated circuits (SLICs) are being developed for integration into antenna packaging.

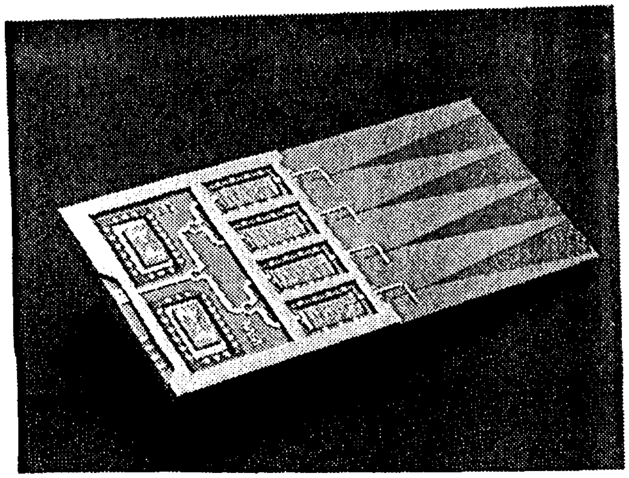

Figure 2. Multi-chip phased array module with integral radiating elements

MATERIALS SCIENCE

Our efforts in material science for high frequency electronic packaging focus on

- development of reliable conductor systems on a variety of substrates,
- integration of thin film capacitors into the packages,
- effective thermal management of high power-high frequency packages,
- environmental protection of packages using organic coatings.

The mechanical properties of thin film conductors as well as their interactions with dielectric substrates are a major source of reliability problems in high frequency packaging, For example, two types of stress intrinsic and extrinic are present in thin films. Intrinsic stress which, is a consequence of the deposition process, can vary from compressive to tensile, depending on the process parameters and is very difficult to predict. The major contribution to extrinsic stress is the thermal expansion mismatch between the conductor and the dielectric substrate. As a consequence of the stress relief process, delamination of the film/substrate interface, splitting of the film, or substrate cracking is observed for coatings in tension. The buckling of the film and the subsequent delamination of the films is associated with the compressive stress. These processes, which take place during thermal cycling or during MCM operation, are a major failure mode in electronic packaging. Chemical interactions and interdiffusion processes between metallic thin films and the substrate could also be a reliability problem. We have developed a novel Cr/CrN/Au conductor system which exhibits reduced intrinsic stress compared to the conventional Cr/Au bilayer. Due to the presence of a CrN diffusion barrier it also exhibits superior chemical and thermal stability. ***We will continue to focus our efforts on the correlation between processing of thin film conductors and substrates and their performance in high frequency packages.***

High-frequency high-density MCM packaging technology imposes some critical restrictions on passive components, namely bypass and decoupling capacitors. The first restriction arises from the fact that the space available for capacitors (both in volume and area) is very limited. The second restriction is dictated by the power distribution and conditioning system. It is thus beneficial to directly integrate thin film bypass capacitors between the power and ground planes of the module. The dielectric constant of both decoupling and bypass thin film capacitors should be high and stable in the high frequency regime, with low leakage current and high breakdown strength. The highest dielectric constant is reported for perovskite ferroelectric capacitors but the deposition temperature or post annealing treatments required to fabricate perovskite structure are relatively high (above 400°C) and thus not acceptable for all MCMs. ***We are in the process of developing of reliable thin film capacitors using deposition techniques which are compatible with manufacturing methods of high frequency multichip modules.***

The effective thermal management of the high-density high-frequency multichip modules is also a major problem, Conventional substrates used in high frequency applications, like alumina ceramics, must be replaced by high thermal conductivity substrates. Commercially available alumina has a good surface finish (about 1 μm) but its thermal conductivity is too low for packaging of high power high frequency devices (25 W/mK). On the other hand, thermal conductivity of commercial aluminum nitride ceramic substrates is high (220 W/mK), but the surface finish is poor (above 3 μm). ***We have developed a new type of substrate for high frequency packaging [7].*** The substrate consists of a highly polished bulk alumina ceramic substrate and a layer of aluminum nitride deposited on top of it using a thin film sputtering technique. The surface finish of the aluminum nitride film is the same as the surface finish of the alumina substrate (1 μm) and its thermal conductivity is one order of magnitude higher than that of alumina. The thickness of the aluminum nitride film can be adjusted to provide a required thermal heat spreading to a thermal sink. This new substrate takes advantage of both the surface finish of alumina and the thermal conductivity of aluminum nitride. Aluminum nitride can be replaced by a diamond substrate or diamond thin film but this technology is currently very expensive.

Current high frequency space electronics use semiconductor chips that are hermetically sealed in ceramic/metal packages. While providing good protection from severe environments, these packages significantly increase cost, mass, and volume of space electronics. Another serious problem associated with hermetically-sealed package materials (such as Kovar or Invar) involves the degradation of GaAs devices resulting from the interaction between hydrogen released from the package and donors in the channel region under the gate of the devices. One solution to this problem is to replace the hermetic package with an environmentally protective barrier coating. ***We are working with industry to develop barrier coatings which will provide a weight/volume reduction by eliminating the welded metal cover from the package, while maintaining the radiation resistance and reliability currently associated with hermetically sealed packages.***

CONCLUSION

High-density high frequency electronic packaging is a key to achieving mass/volume reductions which will enable future NASA/JPL missions and complement the explosion in the commercial communication/computer/information industries. The work described in this paper is the beginning of a long term initiative to accelerate development of this emerging field. The development of accurate software tools, characterization techniques and material knowledge is aimed to help reduce design cycle time and development costs of high frequency packages. By establishing a close interaction with the outside community, we will accelerate the availability of high performance miniature high frequency packages.

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